LIMITED CIRCULATION

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AGRICULTURAL MEMORANDUM No. 1039

A simplified method for calculating potential evaporation.

SUMMARY

The potential evapotranspiration (PE) is an excellent weather parameter for use in agriculture because it is an overall single value variable independent of soil and largely independent of crop type once full ground cover has been achieved. The key input terms for determining PE, ie temperature, sunshine, humidity and wind speed are reasonably consistent over an area which implies nearby rather than on-farm measurements of these parameters may be used. PE together with on-farm measurements of daily rainfall provide a useful measure of the amount and timing for irrigation. This paper provides a simplified equation to derive PE on a daily basis.

INTRODUCTION

When irrigation is properly practiced the translocation of water through the plant system, and the ensuing transpiration, is continuing at its full potential rate and the uptake of nutrients is maximised for the prevailing weather conditions, ie sunshine, temperature, humidity and wind speed. The full potential transpiration plus the evaporation of rainfall and dew from the plant surface is commonly referred to as potential evapotranspiration or simply PE. When an irrigated crop fully covers the ground the PE used with the rainfall provides a useful measure of the amount and timing of the next application of irrigated water.

The PE for grass in particular is a useful parameter because grass fully covers the ground throughout the growing season and other crops such as cereals and sugar-beet have a very similar PE when they achieve full ground cover. At the stages between emergence and full ground cover the PE increases with increasing ground cover.

Since Penman (1948) introduced his impirical-theoretical equation relating evaporation from an open water surface to the environmental conditions steady progress has been made in the theory of evaporation and transpiration. The theoretical equations have become more numerous and more complex, and to the average farmer/grower incomprehensible.

The theoretical models of evaporation and tranpiration have now reached an advanced stage in their development. In particular the Meteorological Office Rainfall and Evaporation Calculation System (MORECS), after Thompson et al (1981), offers a sound basis for determining the PE for any specified crop on a daily basis. Therefore the time is ripe to utilise the MORECS output to develop statistical/empirical equations in order to simplify and quantify the respective contributions of sunshine, temperature, humidity and wind speed to PE.

This paper describes the development of simple empirical equations for determining PE for grassland given the averaged daily temperature and hours of sunshine. When the relative humidity (or vapour pressure)at 0.900 hours and average daily wind speed, or run of wind (10 m), are used with temperature and sunshine the impirical equation is more accurate and typically accounts for over 90% of the variation in the daily MORECS derived values. The small errors are mostly random and tend to cancel each other out over a period of days or weeks.

A 2-PARAMETER REGRESSION EQUATION FOR PE (GRASS)

The MORECS daily PE values for grassland during the period April to September 1982 were used in a regression equation of the form:-

$$PE = A_1T + A_2S + A_3 \qquad (1)$$

Where PE is the MORECS daily PE (mm)

T, the average air temperature °C

S hours of sunshine

and A_1, A2 and A_3 are regression coefficients to be determined.

The PE values were computed by the single station version of the MORECS program with the daily temperature and sunshine data for Shawbury, North Shropshire. Best fit regression coefficients were found by the multiple linear regression technique based on least squares and the coefficients were found to vary in a systematic manner according to the month of year as follows:-

$$\begin{aligned}
\text{PE (April)} &= 0.08T + 0.14S + 0.4 \\
\text{PE (May)} &= 0.11T + 0.18S + 0.4 \\
\text{PE (June)} &= 0.10T + 0.17S + 0.4 \\
\text{PE (July)} &= 0.09T + 0.15S + 0.4 \\
\text{PE (August)} &= 0.08T + 0.13S + 0.4 \\
\text{PE (September)} &= 0.07T + 0.12S + 0.4
\end{aligned} \qquad (2)$$

This pattern of regression coefficients suggested a single equation could be obtained of the form

$$PE = A\,(0.12T + 0.20S) + 0.4 \qquad (3)$$

where the coefficient A varied with time of year. Combining equations 2 and 3 gives monthly values of A as presented in Table I.

TABLE I. Monthly values of 2-parameter Regression Coefficient (A) in Equation 3 and multiple correlation coefficient using Shawbury 1982 dependent data.

Month	A	R
April	0·65	0.72
May	0.90	0.76
June	0.80	0.83
July	0.73	0.80
August	0.65	0.73
September	0.57	0.75

Equation 3 with values of A from Table I is equivalent to, ie another form of, equation 2.

RESULTS FOR THE 2 PARAMETER REGRESSION EQUATION

The accuracy of this 2 Parameter (temperature and sunshine) regression equation for determining daily PE is very good for June and July with multiple correlation coefficients of around 0.8 but decreases for earlier and later months, ie 0.7 in April and September. The reason for this is probably the omission of the wind and the humidity parameters which increase in relative significance as winter is approached. This is confirmed by comparison with the results summarised in Table 5 for the 4-parameter regression equation.

The accuracy of the 2 parameter regression equation 1 for determining daily PE's for grass is demonstrated by comparisons with the corresponding MORECS values using dependent and independent data. First equation 1 was solved for daily Shawbury temperature and sunshine data using MORECS daily PE's April 1982 (dependent data). The resultant equation was then used to derive daily PE's for the very wet month of April 1983 (independent data). A selection of results are given in the last (col 6) column of Table 2. The corresponding PE values obtained with regression coefficients derived from dependent data are given in the second from last column of Table 2. The procedure was repeated for the month of May.

TABLE 2. VALUES OF DAILY PE CALCULATIONS USING MORECS AND REGRESSION EQUATION (4-PARAMETER AND 2-PARAMETER MODEL) WITH DEPENDENT AND INDEPENDENT DATA FROM SHAWBURY. [ ] indicates large errors

DATE	MORECS PE	REGRESSION EQUATION PE			
		4-PARAMETER		2-PARAMETER	
		DEP	INDEP	DEP	INDEP
1	2	3	4	5	6
1983					
7 April	1.7	1.7	1.5	1.6	1.3
8	1.4	1.6	1.5	1.5	1.1
9	1.6	1.7	1.5	1.8	1.8
10	1.3	1.3	1.2	1.3	0.5
11	1.9	1.9	2.1	1.6	1.1
12	2.3	2.3	2.5	2.1	2.3
13	1.4	1.6	1.6	1.5	0.9
14	1.2	1.5	1.3	1.5	0.9
15	1.9	2.0	2.0	2.3	2.5
16	1.7	1.8	1.6	1.6	1.2
17	2.0	2.1	2.1	1.8	1.7
18	1.2	1.0	[0.6]	1.2	[0.3]
19	1.5	1.3	1.1	1.2	[0.5]
13 May	3.1	3.1	3.2	2.6	2.7
14	3.5	3.2	3.2	3.0	2.9
15	2.4	2.4	2.5	2.7	2.8
16	3.1	2.9	2.9	2.7	2.8
17	3.1	3.0	2.9	2.6	2.7
18	2.3	2.5	2.4	2.8	2.8
19	1.7	1.7	1.5	1.8	1.9
20	1.7	1.8	1.7	1.8	2.1
21	1.3	1.2	1.2	1.5	1.7
22	0.5	0.5	0.6	[1.1]	[1.3]
23	1.2	1.1	1.0	1.4	1.5
24	1.9	2.1	2.1	2.3	2.5
25	2.9	2.9	3.0	3.1	3.1

The relatively large error on the 22 May is caused by the omission of the vapour pressure term which was extremely large on this day and severely limited the PE. The errors on 18 and 19 April are caused by a combination of events, eg no sun, very low temperature, high 09.00 hrs vapour pressure and moderate winds. When the 09.00 vapour pressure and mean daily wind speed are included in a 4 parameter regression equation the errors are significantly less, see columns 3 and 4 of Table 2.

An interesting use of equation 3 is to derive monthly PE's using monthly averages of temperature and sunshine for different parts of the country and compare the answers to those given in MAFF Technical Bulletin 35. Table 3 presents the results of doing this for the area of North Shropshire, ie area 18N in Technical Bulletin 35.

TABLE 3. SHAWBURY (North Shropshire)
LONG TERM MONTHLY AVERAGES OF TEMPERATURE AND SUNSHINE AND MODELLED VALUES OF PE FOR GRASS.
(A) AFTER MAFF TECH BULLETIN 35 AND
(B) AFTER 2-PARAMETER REGRESSION BASED ON 'MORECS'

MONTH	TEMP °C	SUN HRS/DAY	(A) PE	(B) PE
JAN	3.6	1.6	7	-
FEB	3.4	2.5	9	-
MAR	5.7	3.5	30	-
APR	8.4	5.1	55	52
MAY	11.5	6.0	80	82
JUN	14.6	6.6	92	89
JUL	16.5	5.5	91	81
AUG	16.1	5.2	71	71
SEP	14.2	4.1	43	55
OCT	10.7	2.9	20	-
NOV	6.4	1.8	9	-
DEC	4.0	1.5	6	-

The 2 parameter regression results, column B of Table 3, are not claimed to be accurate but they do indicate the likely improvements of MORECS long term averages over the earlier PE model. In particular the average annual PE is probably little changed but the MORECS summer maximum will be lower and about a month earlier whilst the autumn decrease will be more gradual as depicted in Fig.1. These differences in the long period monthly averages of PE are directly related to the MORECS use of surface resistance and leaf area index which are tabulated in Table 4 together with the monthly values of the regression coefficient (A) for equation 3.

TABLE 4. MORECS montly value of surface resistance, r (sm^{-1}), and Leaf Area Index (LAI) for grass compared with the corresponding values of the Keers 2-term regression coefficient (A), Equation 3.

MONTH	A	r	LAI
APRIL	0.65	50	4
MAY	0.90	40	5
JUNE	0.80	60	5
JULY	0.73	60	5
AUG	0.65	70	5
SEPT	0.57	70	4

A 4-TERM-REGRESSION EQUATION FOR PE

The temperature and sunshine alone account for 50-70% of the variability in daily PE values for grass but significant improvements can be achieved by including a vapour pressure and wind speed term in an equation of the form.

$$PE = B_1T + B_2S + B_3VP + B_4W + B_5 \qquad (4)$$

where PE is the MORECS daily PE (mm) for Shawbury, North Shropshire

T is the average air temperature °C

S is hours of sunshine

VP is the vapour pressure (mb) at 09.00 GMT

W is the average daily wind speed (knots) from a 10 m high anemometer,

and B_1, ---, B_5 are regression coefficients to be determined.

The regression coefficients which gave the best fit to the MORECS daily PE data for each month April to September are presented in Table 5.

TABLE 5. BEST FIT REGRESSION COEFFICIENT B_1 TO B_5 AND MULTIPLE CORRELATION COEFFICIENT USING 1982 SHAWBURY DATA (DEPENDENT DATA) IN EQUATION 4.

MONTH	B_1	B_2	B_3	B_4	B_5	R
APRIL	0.22	.09	-0.22	.06	0.9	0.96
MAY	0.26	.12	-0.24	.10	0.6	0.97
JUNE	0.30	.12	-0.23	.09	0	0.95
JULY	0.28	.12	-0.20	.09	0	0.96
AUG	0.25	.11	-0.20	.07	0.3	0.90
SEPT	0.23	.09	-0.23	.06	0.7	0.96

The regression equation 4 can easily be modified to calculate weekly or monthly PE by using average daily values of the weather parameters and a multiplying factor equal to the number of days in the period.

RESULTS

The multiple correlation coefficients given in Table 5 illustrate the excellent results obtained using a 4 parameter regression model with dependent data, ie for 1982. To test the stability of the regression coefficients for independent data, ie for other years, the extremely unseasonal weather experienced in April and May 1983 was used as input to equation 4. Some of the results are presented in Table 2 (alongside those for the simpler 2 parameter PE model) and in Fig.2. The periods were specially chosen as representative of the errors which occassionally occur and in particular the error on 22 May is drastically reduced and only the very extreme combination of weather on the 18 April was not handled well.

The chief weakness of the 4 parameter PE model is the use of a single 09.00 GMT value of the vapour pressure which is assumed to represent the daily average vapour pressure. Barrie (1982), has shown how different methods for determining the daily average vapour pressure produces different results and shows that a single 09.00 value method is not as accurate as the MORECS method of averaging the 03.00, 09.00, 15.00, and 21.00 values when these are available such as at a fully staffed Met Office, for example Shawbury.

An analysis of the month by month changes in the regression coefficients given in Table 5 shows the significantly increasing role of temperature and sunshine hours as mid-summer approaches, ie as the solar angle (elevation) increases. This is undoubtedly related to the increasing radiative energy received on horizontal surface as the solar angle increases in addition to the changes in the MORECS surface resistance and leaf area index termsSummarised in Table 4. The coefficient for the wind term, B, is smaller in the windier months because of the larger variability of the wind strength and the requirement to minimise the errors.

PRACTICAL APPLICATIONS

(i) Irrigation Scheduling

The Met Office and ADAS daily balance sheet approach to irrigation scheduling uses daily PE values derived from averages of many years of data; the average daily PE is assumed to change from 1.7 mm in April to 2.7 mm in May and 3.1 mm in June. The daily PE calculated using equation 4 may be used to drastically reduce the daily errors which otherwise accumulate and the weekly or monthly updates using MORECS become much less significant.

The 09.00 GMT vapour pressure and the average daily wind speed (10 m high anemometer) may not be available at some sites and in this case equation 2 may be used to derive daily PE; the reduction in accuracy is indicated in Table 6. The results suggest that the accuracy of the 2 term regression equation increases with increasing variability of input data. Thus the results are best for the summer months when variations of sunshine and temperature are potentially, and usually in practice too, most significant.

TABLE 6. COMPARISON OF MODEL RESULTS - ASSUMING MORECS PE IS THE ACTUAL PE FOR APRIL AND JUNE 1982 AT SHAWBURY

PE MODEL with brief description	Standard Error (mm)		Percentage variation of PE accounted for	
	April	June	April	June
Model 1 (Daily Balance Sheet)	0.6	0.9	30	0
Model 2 (Average T and Estimated Sun)	0.5	0.4	40	50
Model 3 (Average T and measured Sun) Equation 2	0.4	0.3	52	69
Model 4 (Average T, Sun, VP and Wind Equation 5	0.2	0.2	96	95
Model 5 (MORECS, using Shawbury data)	0	0	100	100

(ii) Estimating potential soil moisture deficits (PSMD)

Assuming crops are transpiring at their full potential rate all the time, ie there is no shortage of water throughout, the PSMD may be assessed in terms of its daily accumulative deficiency of water according to the following equation:-

Potential soil moisture deficit (PSMD) = $PSMD_y$ + PE - R (5)

where $PSMD_y$ = PSMD yesterday, PE = the PE over the last 24 hours (using equation 4), and R = rainfall over the last 24 hours. PSMD canot be negative so the PSMD only begins to accumulate some time in the spring season when PE starts to exceed the daily rainfall (R).

In an unirrigated crop the actual evaporation = the PE value until the crop suffers some drought stress. This is different for different crops but in general terms the stomata increasingly restricts transpiration after the SMD reaches about 40 mm but it may be earlier than this for shallow rooted crops such as potatoes or in crops emerging with poor root development. The complex computer models such as MORECS make allowances for different crops and their average sowing dates in different parts of the country, and for the calculation of actual SMD allow for different soil types eg heavy, medium and light soil, through the available water capacity of the 3 main classes.

No attempt has been made in this paper to simplify the calculation of actual soil moisture deficit as opposed to the potential. It is worth stressing, however, that the potential SMD (equation 5) is a good measure of the weather related drought stress in any given season. It is dependent on the type of crop because it accumulates individual daily contributions and naturally the date of crop emergence and the date full ground cover is achieved is critical for the derivation of PSMD using equation 5. Once the crop fully covers the ground the derivation of PE differs very little between grass, sugar-beet, potatoes, etc during the summer months.

(iii) Crops other than grass

The MORECS model will cope with any one of a broad range of crops but in general the output are averages over 40 by 40 km squares covering the country and the input data are from only a small selection of Met Office and subsidiary stations. There is, however, a version of a MORECS comuter program which will run using site specific data when these are available. This is most important when site specific daily rainfalls are much different from the area average values and soil moisture deficits are required rather than PE's.

The MORECS program is not suitable for running on a microcomputer but Spackman (1984) has developed such a programme based on the ideals of MORECS. This allows site specific weather and crop data to be used. The latter is important because the on-farm micro can take account of unusual cropping practices, such as in 1983 when the very wet April and May months delayed the sowing of many spring sown crops. Also site specific soil properties can be used in the program.

Regression models, as for grass in this paper, can be developed for any crop already programmed for in MORECS but as yet this has not been done.

CONCLUSIONS

The daily potential evapotranspiration (PE) for grass may be calculated using a sir;le equation with only temperature and sunshine terms. The accuracy improves if the 09.00 GMT vapour pressure and average daily wind speed is included. The results compare very favourably with those from MORECS although MORECS includes a model for actual evaporation and actual soil moisture deficit in addition to potential values and includes a large range of different crops.

Any comments or suggestions relating to this paper should be addressed to the author.

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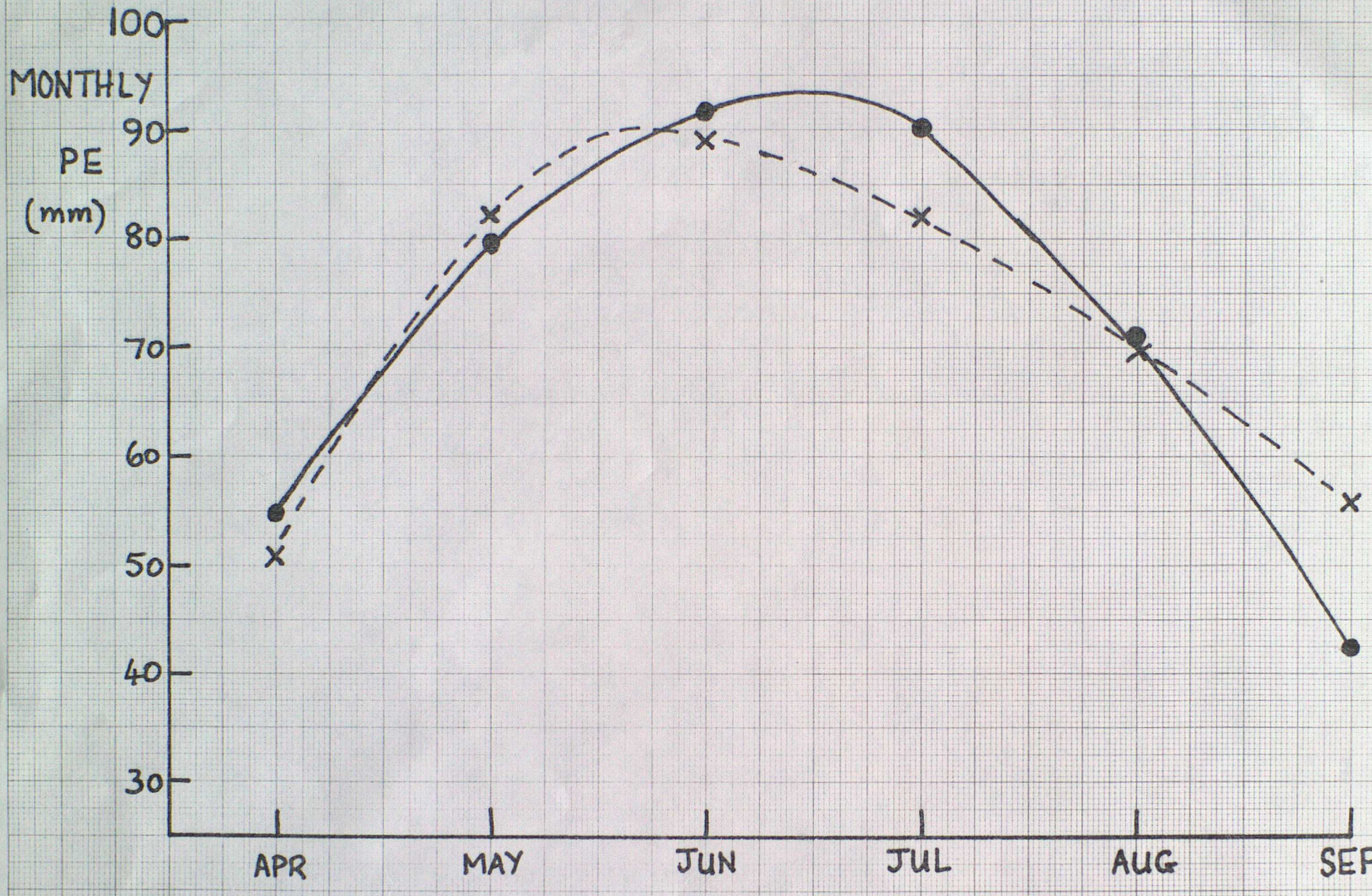

FIG 1. Long term average monthly PE for an altitude of about 400 ft in North Shropshire : ●——● Tech Bull 35, X - - - X 2 parameter regression.

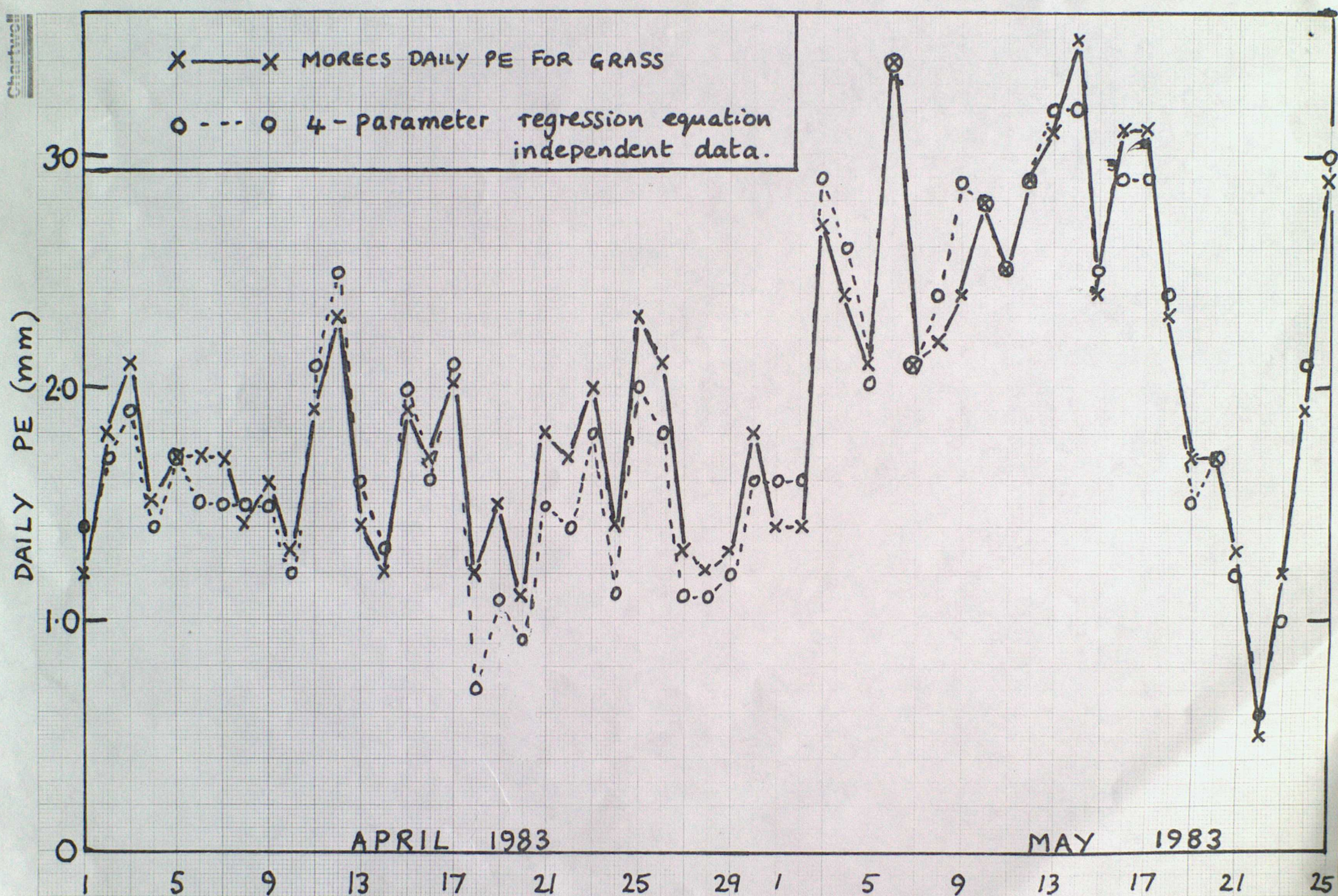
X——X MORECS DAILY PE FOR GRASS
O - - - O 4-parameter regression equation independent data.
DAILY PE (mm)
30
20
10
0
APRIL 1983
MAY 1983
1 5 9 13 17 21 25 29 1 5 9 13 17 21 25

FIG 2. MORECS DAILY PE (SHAWBURY) COMPARED WITH 4-PARAMETER REGRESSION EQU.